Review Article

Potential for Application of Retroreflective Materials instead of Highly Reflective Materials for Urban Heat Island Mitigation

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Research on urban heat island (UHI) mitigation has been carried out globally. Several strategies have been proposed or developed to mitigate UHI, including highly reflective (HR) envelopes of buildings, green roofs, urban vegetation, shading, heat sinks, and air-conditioning efficiency. Among these techniques, HR envelopes have been extensively studied as an effective method to mitigate the UHI effect by reducing energy consumption. However, because most of HR materials are diffusive, HR envelopes applied to vertical surfaces can reflect both onto roads and nearby buildings. Additionally, HR roofs cannot reflect all incoming solar radiation to the sky if there are high buildings around it. Thus, HR materials applied as building envelopes have a limited effect against the solar contribution to the UHI. In order to solve this problem, retroreflective (RR) materials, which reflect the solar radiation back towards the source, have been studied and developed to be applied as building envelopes instead of HR materials. This paper summarizes several previous researches on HR envelopes and cool roofs and summarizes several current researches on RR materials. The potential for application of RR envelopes in cities is proposed with consideration of economic and environmental factors.

1. Introduction

The urban heat island (UHI) effect is a serious challenge to energy conservation in urban centers in urban canyons over the summer period. A significant spatial and temporal variation is observed in the UHI intensity; many cities show a temperature 5–10°C higher than surrounding rural areas by midmorning [1]. The UHI effect could lead to increases in energy consumption for cooling [2], increased peak electricity demand [3], and degraded air quality [4]. Countermeasures to mitigate the UHI effect are being implemented by many researchers around the world [5–9].

As one of the most effective measures to reduce the UHI effect and an acknowledged solution for energy savings, highly reflective (HR) envelopes applied as building external walls have been investigated in several countries [10–15]. HR roofs have similarly been studied widely [16, 17]. HR roofs can reflect solar radiation to the sky if there are no high buildings around it. However, if there are high buildings nearby, part of the reflection will be absorbed by those neighboring buildings. HR envelopes applied to vertical surfaces can also

reflect onto roads, causing them to become hotter, so the total effect against the UHI is limited. To solve this problem of HR materials used for vertical outer walls, a variety of retroreflective (RR) materials began to appear on the market that can reflect the incident solar radiation back towards the source. However, those RR materials are mainly employed for various safety and decorative purposes, for improved visibility under low light conditions. They are not commercially available for application to building envelopes in Japan. The application of RR materials as new urban coatings is a novel research field and has some potential to (i) reduce the heat content in the UHI boundary; (ii) reflect solar radiation beyond the urban canopy; (iii) reduce the interbuilding effects in terms of mutual reflection. Glass beads and prism-arrays are the common main components of RR materials. In order to encourage use of RR materials more widely, the RR properties of these materials and the thermal-energy impact of these RR building envelopes are being studied internationally [16, 18–23].

Solar reflectance of building envelopes and urban pavement represents an important optic-energetic property for

TABLE 1: Summary of influence of HR envelopes on the surface temperatures.

Reference	Methodology	Surface temperature change
[30]	Using CFD simulation and TRNSYS.	In a typical summer period, the surface temperature decreased up to 12°C.
[31]	Using weather research and forecasting (WRF) v3.2.1 model.	Summer afternoon temperature in urban locations reduces by 0.11–0.53°C and some rural locations show temperature increases of up to 0.27°C.
[32]	Monitoring roof surface units by experiment.	Daytime temperature of gray paint is almost 10°C higher than that of white paint in August.
[33]	Installing a cooling roof and measuring temperature and so forth.	From April to September, temperature of roof decreased up to 20°C.
[34]	Monitoring white and black roofs.	On a warm day, a reduction of 26°C by white roof in midafternoon occurs.
[35]	Applying reflective roofs on two small nonresidential buildings and measuring temperature and so forth.	Average reduction of about 10°C in daytime during the summer period occurs.
[36]	Using energy balance model.	Temperature reduction of up to about 15°F in July occurs.
[37]	Using TRNSYS software.	Temperature reduction of up to 25°C during summer occurs.

the characterization of building energy performance for cooling and to mitigate the summer UHI effect [24–28]. The solar reflectance of a building envelope can be calculated by means of spectrophotometer measurement of the material itself and knowing the solar radiation absorbed by the building envelope. Corresponding to solar reflectance of diffusive building envelopes, retroreflectance refers to the ability of a specially engineered surface to preferentially reflect incident sunlight back towards its source. Methods to derive the retroreflectance of RR materials are summarized by many researchers, and the effects of RR envelopes on building energy saving are also examined by simulations [16, 18, 19, 22, 23]. However, there is still little research on practical application of RR materials for building external walls.

This paper reviews previous research on HR envelopes, such as the effect of HR envelopes on environment temperatures, effect of HR envelopes on building energy consumption, and effect of HR envelopes on UHI intensity. Second, because HR envelopes have some drawbacks on reflective direction, being not able to reflect the incoming sunlight on building external envelope back towards the source, the objective of this paper is to provide a synthetic overview of application possibility of RR envelopes instead of HR envelopes in cities with consideration of economic and environmental factors.

2. Influence of HR Envelopes on the Surface Temperatures

Solar reflectance or retroreflectance of building envelopes determines the amount of solar radiation reflected from the building external envelope. The effect of HR materials has been examined in many previous researches, especially the effect of HR envelopes on the building surface temperatures [29–36]. Table 1 summarizes the main results of researches on impacts of HR materials on surface temperature in simulations and experiments.

The work in the Athens area by Santamouris et al. [29] shows that the use of cool pavements contributes to decreasing the peak ambient temperature during a typical summer day, by up to 1.9°C, and the surface temperature in a park was reduced up to 12°C in parallel. The overall analysis shows that use of cool pavements is an efficient mitigation strategy to reduce the strength of UHI effect.

Millstein and Menon [30] used the weather research and forecasting (WRF) model to investigate feedback between surface albedo changes, surface temperature, precipitation, and average cloud cover. It shows that the afternoon summertime temperature in urban locations was reduced by 0.11–0.53°C with the adoption of cool roofs and pavements.

Observations by Takebayashi and Moriyama [31] show that the daytime temperature of HR gray paint on building roof is almost 10°C higher than that of HR white paint in August. The surface temperature of a green roof is several degrees lower than that on bare soil surface, and it is several degrees higher than that of HR white paint. However, the surface temperatures of a green roof and bare soil are approximately the same in November. It is considered that, due to evapotranspiration, the surface temperature of a green roof in summer is lower.

The experimental work related to a cool roof application on a 700 m^2 roof in Trapani, Sicily, was carried out by Romeo and Zinzi [32]. The results show that roof temperature decreased by up to 20°C from April to September, and average indoor air temperature reduced by 2.9 and 3.1°C in two studies rooms. The cooling and total net energy demand also decreased by about 3.8%, due to the cool roof.

Simmons et al. [33] constructed a total of 24 experimental roof platforms in Austin, Texas, representing black, nonreflective roofs, white reflective roofs, and six different green roof designs, to compare their roof temperatures. It showed that maximum green roof temperatures were cooler than conventional roofs by 38°C at the roof membrane and 18°C inside air temperature. Also the experiment showed that white reflective roofs are at average 26°C cooler than black roofs in midafternoon on a warm day.

Akbari's work [34] applied reflective roofs on two small nonresidential buildings with roof area of 14.9 m^2 during summer of 2000. The original solar reflectivity of roofs was about 0.26. After the application of roof coatings, the reflectivity was increased to about 0.72. The result of this experimental work showed that the average roof temperature decreased about 10°C in daytime in summer. Additionally, it showed that a reflective roof could save energy at no incremental cost.

Gaffin et al. [35] constructed a general energy balance model applicable to both green and nongreen roof surfaces. In this study, the Penn State Center for Green Roof Research has developed and instrumented a green roof field experiment in Central Pennsylvania. The experiment consists of 6 separate buildings, 3 with green roofs and 3 with control dark roofs. The experimental results showed that the average temperature of green roofs was about 15°F lower in July.

An experiment increasing solar reflectance of the roof surface of a noncooled school building in Athens was carried out by Synnefa et al. [36]. A monitoring campaign was carried out before and after the application of a white elastomeric coating with a solar reflectance of 0.89. The surface temperature of the building was measured, and the building was modeled into TRNSYS software and the model has been calibrated and validated using the experimental data. Simulation results showed a decrease in the air temperature of up to 2.8°C in the classrooms and surface temperature reduced up to about 25°C during summer period.

These findings show that green roofs or HR envelopes can reduce the surface temperatures of buildings; however, the thermal interactions between pavements and nearby objects need special attention due to their diffusive reflective properties. This interaction may not be seen as a problem in open areas, but it tends to be more serious in high density urban centers where walls are close to pavements or neighboring buildings. Thus, the lack of the previous research is less for the application of HR materials on the façade of buildings and the application of RR materials on the building envelopes. The RR material should mitigate the UHI effect if put into practice.

3. Influence of HR Envelopes on Building Energy Consumption

The global contribution from buildings towards energy consumption, both residential and commercial, has steadily increased to between 20% and 40% in developed countries and has exceeded the other major sectors: industrial and transportation [37]. Recently, efforts in reduction of primary energy consumption in the consumer business sector and university facilities have been examined [38–40]. During the past century, global population has become increasingly urbanized and turned cities into large energy consumers. Building energy consumption in cities is closely related to environmental temperature, where there are increased UHI intensity and heat wave events. Land use, land cover modification, and changes in global and regional climate patterns have led to increases in energy demand. Akbari et al.

[41] reported that, for the U.S. cities with populations larger than 100,000 people, peak electricity load will increase by 1.5–2.0% for every 1°F increase in ambient temperature.

Many researches related to the impact of HR envelopes on the energy consumption have been carried out. These are summarized in Table 2.

Georgescu et al. [42] used the advanced research version of the weather research and forecasting model coupled to an urban canyon model (WRF3.2.1) to compare several plausible urban growth futures with climate change effects. They offer an extensive exploration of ranges of impacts and adaptation strategies. It showed that the winter heating penalty of HR coatings can reduce or even exceed the cooling energy savings in summer.

Akbari et al. [43] used the DOE-2 building energy simulation program to investigate the impact of roof reflectivity on cooling and heating energy use for buildings in the U.S. Savings are estimated for 11 US metropolitan statistical areas in a variety of climates. It showed that the largest savings for individual buildings were found in cities with the hottest and sunniest climates. Savings decreased as the climate gets cooler.

Levinson and Akbari [44] combined building energy simulations, local energy prices, local electricity emission factors, and local estimates of building density to characterize local, state average and national average cooling energy savings, heating energy penalties, energy cost savings, and emission reductions per-conditioned roof area (CRA) and per-land area (LA). The result was the potential annual rates of energy cost savings in 236 cities across the US after installing the cool roof. Additionally, Levinson and Akbari used the DOE-2.1-E model with a roof assembly heat transfer module to predict that a cool roof almost always reduced the annual cooling load more than it increased the annual heating load per-CRA, with the greatest saving in Hawaii and the least in Alaska.

Yaghoobian et al. [45] applied the Temperatures of Urban Facets in 3D (TUF3D) model and found that the low albedo of artificial turf (AT) relative to the other materials under investigation results in a reduction in shortwave radiation incident on nearby building external walls and an approximately equal increase in longwave radiation. Consequently, the overall building design cooling loads near AT decrease by 15%–20%.

Zinzi and Agnoli [46] used EnergyPlus software to analyze the impact of cool and green roofs on the overall energy performance of buildings in different localities at Mediterranean latitudes. The numerical comparative analysis shows that the annual energy savings vary from −13.7% to 41.7% by cool and green roofs.

Bianchi et al. [47] used Oak Ridge National Laboratory's Simplified Transient Analysis of Roofs (STAR) computer code to predict the transient heat gain and structure temperature. The numerical code was developed and used to generate the hourly temperature and heat flux through the thickness of insulation over an entire year. Results showed that the cool roofs can reduce the cooling loads by about 38% and increase the heating penalty by about 8.1% in Climate Zone 12 (Sacramento).

TABLE 2: Summary of influence of HR envelopes on energy consumption.

Reference	Methodology	Building type/region	Energy consumption
[42]	Using WRF modeling system.	Urban regional climate simulations in U.S.	Winter heating penalty can reduce and roll back or even exceed cooling energy savings in summer.
[43]	Using DOE-2 model.	Residential and commercial simulation buildings of 11 U.S. metropolitan statistical areas.	The total savings for all 11 metropolitan statistical areas are annual electricity savings, 2.6 TWh; peak electricity demand savings, 1.7 GW.
[44]	Using DOE2.1-E model.	Four commercial building prototypes simulations in 236 US cities.	3.3–7.69 kWh/m^2 energy saving for annual cooling, 0.003–0.065 therm/m^2 heating penalty for 236 cities in U.S.
[45]	Applying the Temperatures of Urban Facets in 3D (TUF3D) model.	TUF3D model simulation domain with buildings and ground with 25 buildings in Southern California.	Overall building design cooling loads near artificial turf (AT) decrease by 15%–20%. The irrigation water conservation with AT causes embodied energy savings of 10 Wh/m^2·day. Radiative energy from ground to wall increases with increasing the albedo of the nearby ground materials.
[46]	Using EnergyPlus software.	Residential simulation buildings in different localities at Mediterranean latitudes.	Annual energy savings range from −13.7% to 41.7%.
[47]	Applying Simplified Transient Analysis of Roofs (STAR) computer code.	Simulations in 16 California climate zones.	Cooling load decreased by about 38% per year; heating penalty increased by about 8.1% per year for Climate Zone 12.

These studies above show that the HR envelope, including cool and green roofs (roof covered with plants), can reduce the energy consumption of buildings for cooling loads in summer. However, it can increase the heating penalty of buildings in winter. Thus, in order to solve this problem that may increase the heating loads in winter, the measure of applying the combination of thermal insulation and cool envelope of building external walls was proposed to minimize the energy consumption of buildings. In addition, as water stress due to climate change and population growth worsens [49], it becomes more difficult and costly maintains the water supply to manage the green roofs. Therefore, instead of a green roof, the application of more effective HR or RR roof is strongly encouraged to save energy of buildings and UHI mitigation.

4. Potential of Application of RR Materials for Building Envelopes

RR materials reflect much of the incoming sunlight back to the incident direction, as shown in Figures 1(a) and 1(b). If applied to building external walls, the RR envelope would prevent much of the reflection of light to roads and surrounding building caused by HR envelopes, as shown in Figures 2(a) and 2(b). Thus, RR envelopes should help to mitigate the UHI, while still having the same potential for energy savings as an HR envelope.

4.1. Methods to Determine Retroreflectance of RR Materials. Before applying RR materials for building external walls, the RR performance has to be analyzed in detail. For methods to determine the retroreflectance of building envelopes, many researchers have defined it through means of experiments and models. Also the impacts of RR envelope on energy consumption of buildings and UHI mitigation were examined globally. The research on RR materials carried out by different researchers was summarized in Table 3 and stated as follows.

Akbari and Touchaei proposed calculating the hourly reflectance of directional reflective materials (DRMs) by using a developed model as a function of zenith and azimuth angles [16]. Two main options are proposed for labeling: one is using one reflectance for the whole year, and the other is using seasonal reflectance, including summer reflectance, winter reflectance, and mean reflectance of summer and winter. A simple method based on seasonal reflectance was proposed, assigning the average reflectance of DRMs as the winter reflectance and the reflectance of the DRM according to a 20° zenith towards the reflective side as the summer reflectance. Errors of estimated energy saving were calculated separated by summer and winter.

Rossi et al. [18] assessed the angular reflectance of 5 types of RR films for several inclination angles of solar radiation from 10° to 80° in steps of 10° interval, by using an *ad hoc* experimental setup, and evaluated RR materials' potential for UHI mitigation by a 2D analytic model.

Nishioka et al. [22] evaluated the directional reflective performance of RR materials configured by a three-mirror and a four-mirror type of corner, using geometrical optical principle. The RR effective area of three-mirror or four-mirror type of corner reflectors was defined, and the relationship between the incident angle and the RR effective area was also examined. However, there was no specific discussion on the energy saving of buildings and UHI mitigation.

Yuan et al. [19, 20] proposed a method to determine the retroreflectance of RR materials by subtracting the
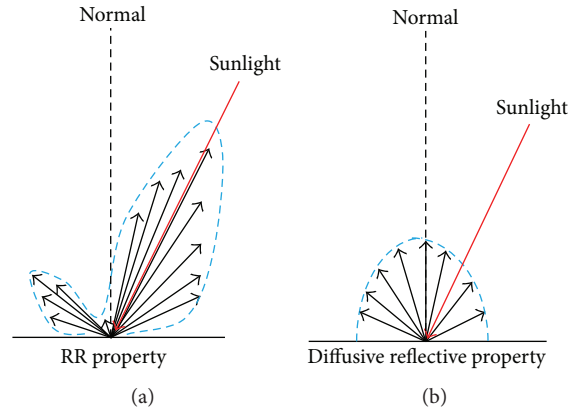
FIGURE 1: Reflection directivity characteristics of RR material and diffusive reflective material ((a) RR material; (b) diffusive reflective material).
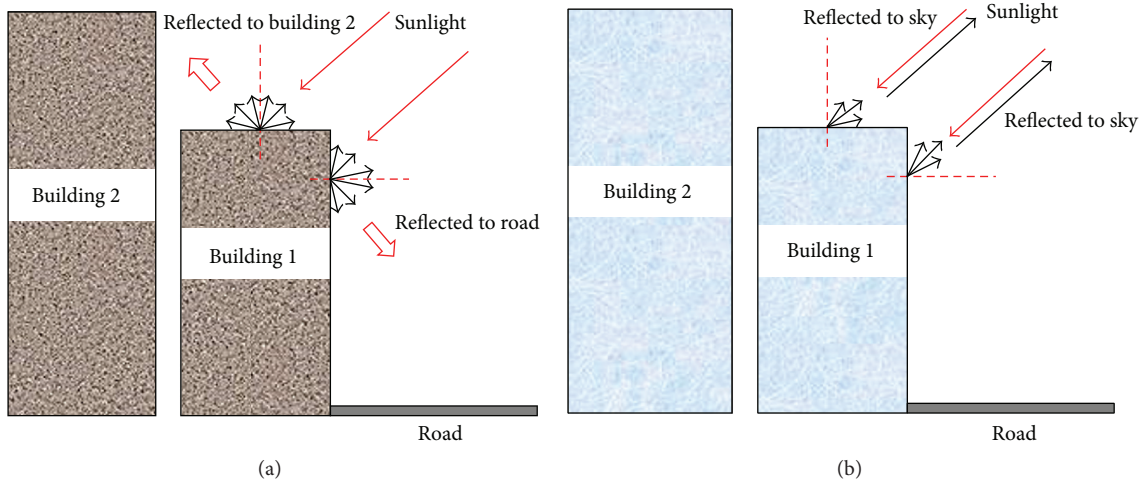

FIGURE 2: Example of solar radiation reflected by two types of building coatings ((a) diffusive HR coatings; (b) RR coatings).

solar reflectance measured with spectrophotometer from the solar reflectance evaluated by the thermal balance from temperatures measured in the outdoor environment. The error of retroreflectance takes into account the wind speed measurement of 2%, which yields an error of up to 0.004 in the solar reflectance evaluated by the thermal balance in Yuan's method [19]. The experimental reflective plate was taken into account as the main error and a revision method for retroreflectance was also proposed by Yuan et al.'s research [48].

The research by Han et al. [23] has evaluated the impact of RR envelope on surface temperature and primary energy for heating and cooling, using simulations and EnergyPlus software which is an energy analysis and thermal load simulation engine distribution by the U.S. Department of Energy. The average temperature reductions of the control building surface during daytime at typical seasonal days in Miami and Minneapolis cities were examined between RR testing and regular diffusive façades by simulation numerical analysis. The analyzed result showed that the average temperature of simulation building envelopes when RR pattern diffusive wall

was used for testing surface is about 0.46°C lower than it of condition when a regular diffusive wall was used for testing surface during daytime at typical summer days in Miami and about 0.42°C reduction in Minneapolis.

4.2. Potentiality of RR Materials for UHI Mitigation by Simulations. RR envelopes could contribute to reduce the energy consumption of buildings and the UHI effect, because a part of the solar radiation is sent back towards the incoming direction [18, 20, 26]. In particular, RR envelopes can strongly reduce the mutual radiative effect among buildings located in close proximity [23].

Yuan et al. [20] have developed a type of RR materials and investigated its durability and RR performance by evaluating changes in retroreflectance for a long time period exposed to the outdoor environment. The influence of different reflective characteristics on the albedo of urban canyons was simulated and analyzed. The results showed that the albedo of simulated urban canyons with RR envelopes is the largest, about 6.1% larger than those with diffusive reflective envelopes and about 9.4% larger than those with mirror reflective envelope.

TABLE 3: Summary of several current studies of RR materials applied for building envelopes.

Reference	Method to derive retroreflectance	Energy saving, urban albedo, UHI mitigation, and so forth
[16]	Model to calculate the hourly reflectance of directional reflective materials (DRMs) as a function of zenith and azimuth angles.	In summer, the selected metric estimates the mean energy saving for building energy models accurately and the peak heat absorption of surface by 8% (<40 W/m^2) error. In winter, the potential energy savings of buildings are overestimated by an error of less than 20%, and mean hourly and peak heat absorptions are estimated by the error of 22 kJ/m^2 and 9 W/m^2, respectively.
[18]	An *ad hoc* experimental setup was designed and used for assessing the angular reflectance of RR films.	The potential of RR materials for mitigating UHI was estimated in terms of cooling potential, defined as a decrease of circulating energy contributing to the canyon overheating, through a 2D algorithm. The decrease of the energy kept inside the canyon due to the use of RR materials has been evaluated for three values of latitude (30°, 40°, and 50°) with a south-exposed façade. In addition, the effect of RR materials on the energy circulating inside the canyon has been evaluated also for different façade exposures (south, east, and west).
[22]	Using two sorts of a 3-mirror type and a 4-mirror type of corner reflectors and geometrical optical analysis method to evaluate the reflection performance to the direct-beam solar radiation and RR properties of RR materials.	The RR effective area of 3-mirror or 4-mirror type of corner reflectors was defined, and the relationship between the incident angle and the RR effective area was also examined. However, there was no specific discussion on the energy saving of buildings and UHI mitigation.
[19, 20, 48]	A method of using spectrophotometer measurement and thermal measurement in the outdoor environment.	The urban albedo was carried out by using a simple 2D shape and Monte Carlo theory, with different reflective characteristics of building envelope materials. The results showed that the RR envelope of buildings is more effective to increase the albedo of urban canyons than the other diffusive or mirror reflective envelopes. Also the impact of RR envelope on thermal loads of buildings was examined by simulation building and New HASP/ACLD-β. The results indicated that RR building envelopes can decrease the annual cooling loads as well as the annual total thermal loads and increase the annual heating loads.
[23]	Using simulations and EnergyPlus to evaluate the impact of RR envelope on surface temperature and energy saving.	The average temperature reductions of the control building surface during daytime at typical seasonal days in Miami and Minneapolis cities were examined between RR testing and regular diffusive façade by simulation numerical analysis. A cross-regional energy analysis of eight cities in U.S. was also examined by simulation numerical analysis.

Rossi et al. [18, 26] have evaluated the mitigation effects of RR materials in UHI scenarios by experimental campaign and a novel analytical model. Five RR samples and one diffusive sample were chosen and their reflection directivity characteristics were tested. As discussed by Rossi et al.'s studies, all RR samples show an RR behavior only for low incidence angles of sunlight. Then for higher angles of incidence, the radiation is mainly specularly reflected. The potentiality of RR materials for mitigating UHI was estimated in terms of cooling potential. Comparing the cooling potential of a RR envelope to a diffusive reflective envelope, it showed that the cooling potential of a high-intensity prismatic RR sample with south-facing is about 1.5% better for latitude of 30°, evaluated by the analytical model.

In order to describe the potential impact of the RR material on energy behavior, Han et al. [23] have used EnergyPlus software to analyze the thermal-energy impact in neighboring buildings in an urban context where buildings are in close proximity. Due to different reflective façades with RR and regular diffusive characteristics, a cross-regional energy analysis of eight cities was examined. It revealed reductions of cooling energy consumption under the RR context for both total energy consumption and cooling energy consumption of HVAC, by up to 8.2% and 9.8% in different metropolitan areas. The result showed that a bioinspired RR façade can reduce the energy required for cooling loads of buildings and lessen the reflected heat of solar radiation in spatially proximal buildings leading to reducing the UHI effects.

4.3. Potentiality of RR Materials by Economic Analysis. In order to put RR materials into practice as a building envelope,

RR materials not only have better reflective directional properties compared to HR materials, but also meet the low cost from the viewpoint of economics. However, the benefit of RR over HR is to the neighboring buildings, not to the occupants of the building which installs RR envelopes. As costs for RR are likely higher than HR, there is little incentive to the individual building owner. Yet, if all buildings install RR, all occupants and the entire city would benefit. Thus, the calculation of economic benefit from RR envelopes should be on the urban planning scale. Based on the analysis method to definite the optimum insulation thickness from considering the cost of building external walls [50–53], we proposed a method to determine the economic benefit of RR materials in this paper, as described in detailed steps:

(i) First step: to determine the optimum overall reflectivity of RR materials for different geographical locations through calculating the annual cooling load of buildings.

(ii) Second step: to investigate the price of RR materials with the optimum overall reflectivity in local commercially available material market.

(iii) Third step: to consider the combination of RR materials and insulation materials for reducing the total thermal loads of buildings.

(iv) Fourth step: to analyze the total cost per unit area of external wall (C_t) over the building envelope lifetime (n) that includes the cost of insulation material (C_{ins}), RR material (C_{ret}), and energy consumption (C_{ene}) in the local market.

(v) Fifth step: to find the lowest total cost of building external walls (C_t) with the optimum RR material.

The total cost per unit area of external wall (C_t) is given by the following equation:

$$C_t = C_{\text{ins}} + C_{\text{ret}} + C_{\text{ene}} = L_{\text{ins}} \cdot c_i + C_{\text{ret}} + c_e \cdot \text{PWF}, \quad (1)$$

where C_{ins} is the cost of the insulation material, C_{ret} is the cost of RR material of building envelope, C_{ene} is the cost of energy consumption over the building envelope lifetime, L_{ins} is the insulation thickness, c_i is the cost of insulation material per unit volume, c_e is the current annual total lifetime cost of energy, and PWF is the present worth factor [54].

The current annual total cost of energy (c_e) is calculated separately for the heat gain (cooling load) and the heat loss (heating load), and it is shown in

$$c_e = W_e \cdot E,$$
$$W_e = W_{e,c} + W_{e,h},$$
$$W_{e,c} = \frac{Q_g}{P_c}, \quad (2)$$
$$W_{e,h} = \frac{Q_l}{P_h},$$

where W_e is the total energy consumption per unit area, E is electricity rate in US dollars per kWh, $W_{e,c}$ is the annual energy consumption for cooling per unit area, $W_{e,h}$ is the annual energy consumption for heating per unit area, Q_g is the total heat gain per square meter per year (the cooling load), Q_l is the total heat loss per square meter per year (the heating load), P_c is the average coefficient of performance (COP) of the air-conditioning system for cooling, and P_h is the average COP of the air-conditioning system for heating.

Total cost is evaluated together with the present worth factor PWF for the building envelope lifetime of n years. The PWF depends on the inflation rate in energy cost r_i, and the interest rate r_d. Equations for deriving PWF are shown in the following equations.

In case $r_i \neq r_d$, then

$$\text{PWF} = \left[\frac{(1 + r_i)}{(r_d - r_i)} \right] \cdot \left\{ 1 - \left[\frac{(1 + r_i)}{(1 + r_d)} \right]^n \right\}. \quad (3)$$

In case $r_i = r_d$, then

$$\text{PWF} = \frac{n}{(1 + r_d)}. \quad (4)$$

These above parameters used in calculating C_t are based on market cost and conditions of RR application locations.

The total of C_t for buildings in a chosen area, from the scale of part of a single urban canyon affected by one building installing a RR envelope to an entire city district installing RR envelopes in all buildings would show the net benefit. This could then be a guide to government or energy companies in creating financial incentive plans to encourage installation of RR envelopes.

As the conditions vary widely (material and energy cost, building size, urban geography, climate conditions, etc.), the results could show whether RR envelopes can be economical or of what price level they become so.

5. Conclusion

While the HR material applied as building envelope has become popular as an important UHI mitigation strategy, its relevant impacts, especially on the surface temperature of surrounding buildings and energy consumption of buildings, are not clearly classified or summarized and vary widely depending on conditions. Therefore, we summarized recent research advances of HR envelopes on reducing the UHI effect from many previous studies in this review paper. Although HR envelopes can mitigate the UHI effect and reduce the energy consumption of buildings, there are still many defects for HR envelopes in terms of UHI mitigation and energy saving of buildings, which are known through previous studies and shown as follows.

(i) HR envelope can reflect some solar radiation to the sky and also onto neighboring buildings and roads. If there are high buildings nearby, even more of the reflection by HR envelopes will be absorbed rather than being reflected to the sky. Thus, HR envelopes have a limited effect against the solar contribution to

the UHI. HR materials are commonly applied to the roof of buildings. However, its application to vertical walls of buildings is not widely implemented at present. RR materials would avoid this issue yielding greater UHI mitigation by application to external walls.

(ii) As urban water supplies are expected to be increasingly stressed worldwide, the maintenance of green roofs will become more difficult. Thus, the development of more effective HR materials of roofs, rather than use of green roofs, is strongly encouraged to mitigate the UHI effect and reduce energy consumption of buildings.

(iii) HR envelopes can reduce the energy consumption for cooling load in summer but may increase the energy consumption for heating load in winter, especially in locations with cold winter. Therefore, the combination of HR envelopes for reducing cooling load of buildings in summer and thermal insulation of external walls for decreasing heating load of buildings in winters should also be considered and proposed as an effective countermeasure to reduce the total thermal loads of buildings.

(iv) Influence of RR envelope and diffusive HR envelope on UHI mitigation regarding the cooling potential or albedo of urban canyons has been compared in simulations. The simulations showed that the RR material is more effective than the diffusive HR material in terms of reducing cooling energy consumption of HVAC and increasing albedo of urban canyons.

In summary, based on several opinions mentioned above, more efficient RR materials which can reflect the solar radiation back towards the source are encouraged to be applied as building envelopes instead of HR materials, especially, for the application to the façade of buildings. In addition, taking into account the adverse effects of reflective materials on the heating load in winter, the optimum combination of RR envelope and thermal insulation of external walls must be better considered to minimize the energy consumption of buildings from the economic analysis due to regions with different climatic characteristics in the future research. Because RR materials prices can widely vary worldwide, are generally not available in commercial form for application to building external walls, and have not been long-term tested for durability in such use, it is difficult to carry out a generally applicable cost analysis. In specific markets, it may be possible as outlined here. Looking beyond the potential for UHI mitigation and energy saving of urban constructions, city planners and policy makers should not only be aware of but also set up standards in quantifying potential environmental impacts of RR materials in addition to or in place of HR materials.

Highlights

(i) We summarized impact of HR envelopes on the surface temperature from several previous studies.

(ii) We summarized impact of HR envelopes on energy consumption of buildings from previous studies.

(iii) We reviewed main methods to determine retroreflectance of RR materials from several current studies.

(iv) We reviewed simulations showing the potential of RR materials for UHI mitigation and energy savings.

(v) We stated viewpoint of applying RR materials to façade of buildings considering environmental factors.
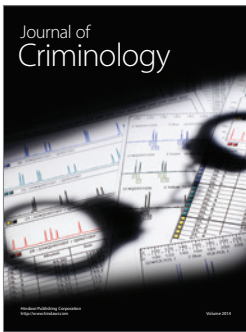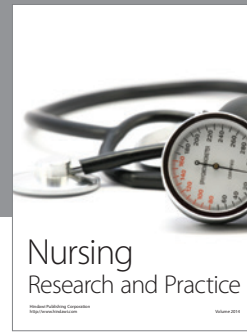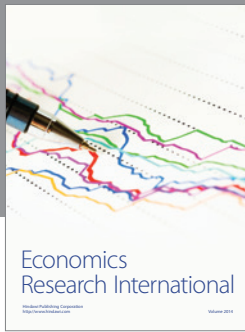
Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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